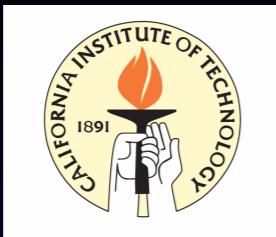
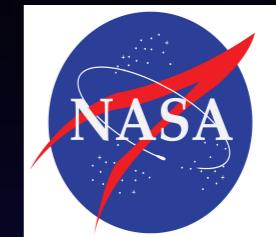


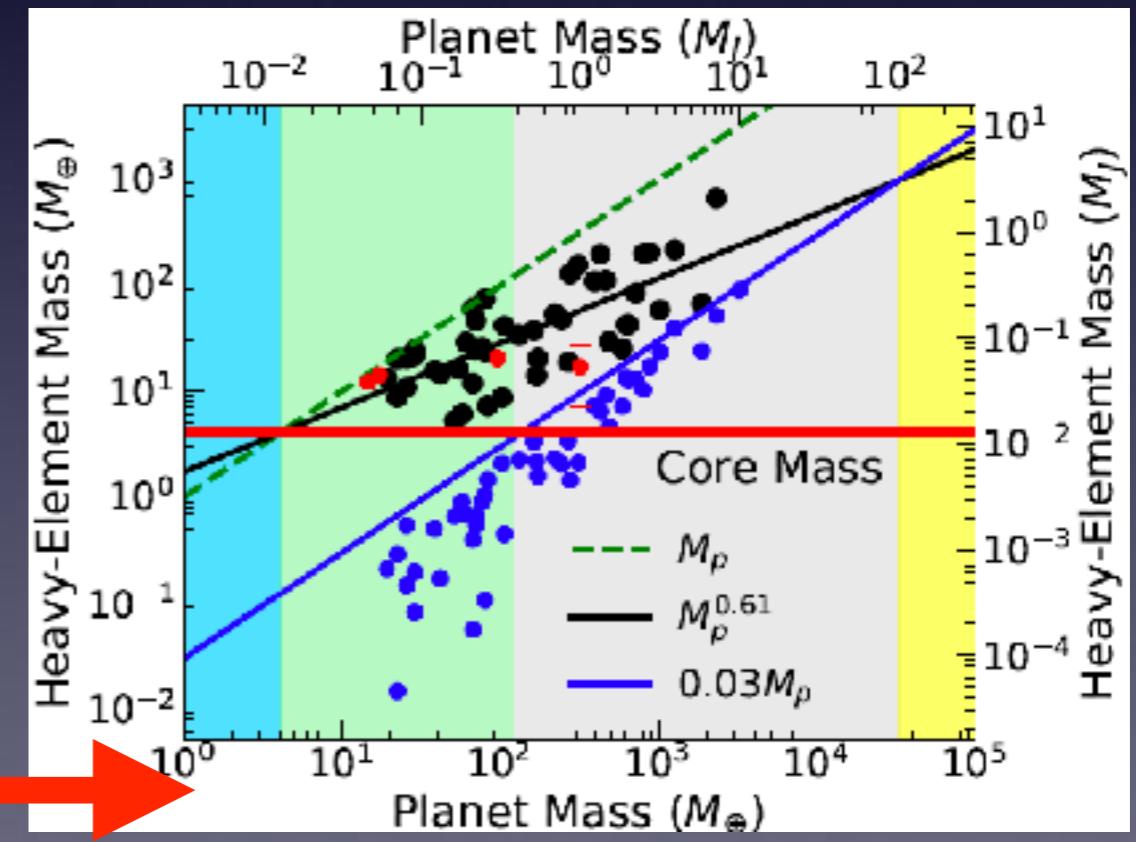
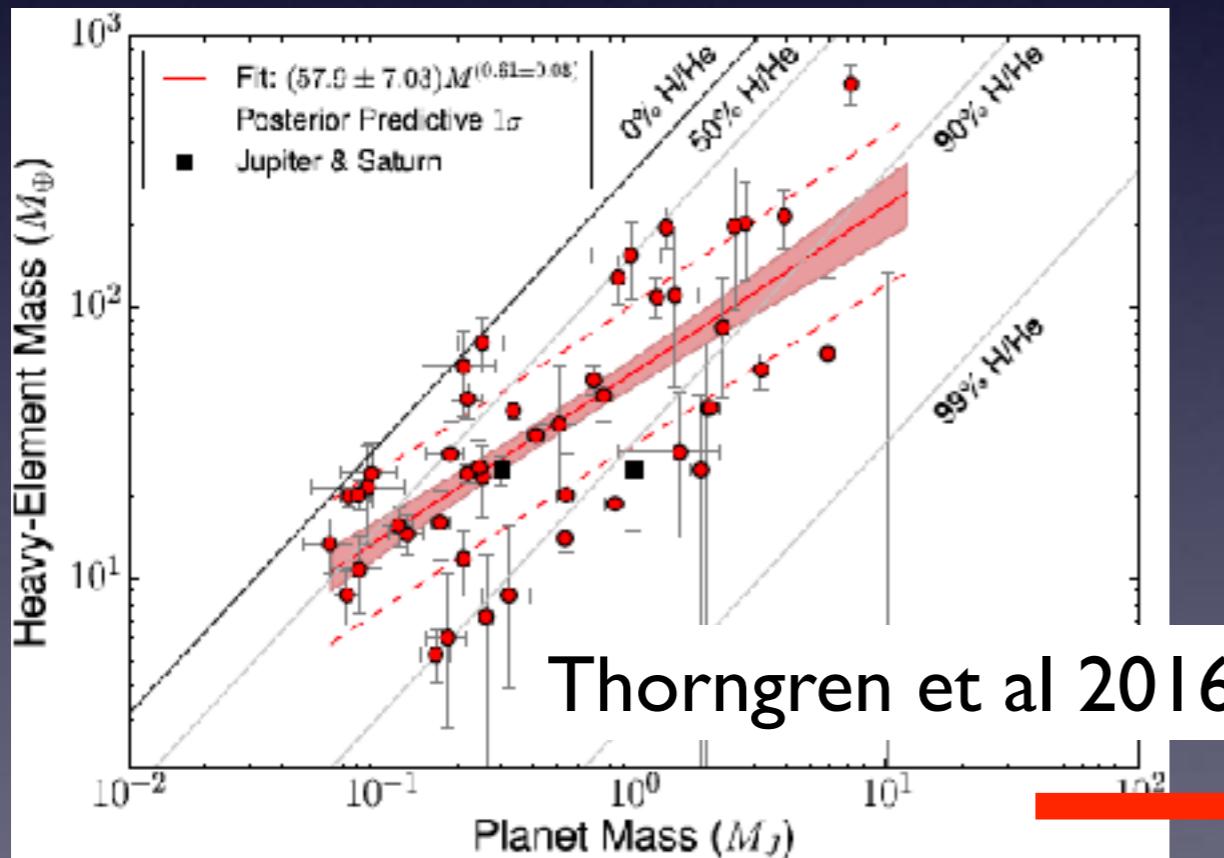
# The Origin of the Heavy Element Content Trend in Giant Planets



Yasuhiro Hasegawa



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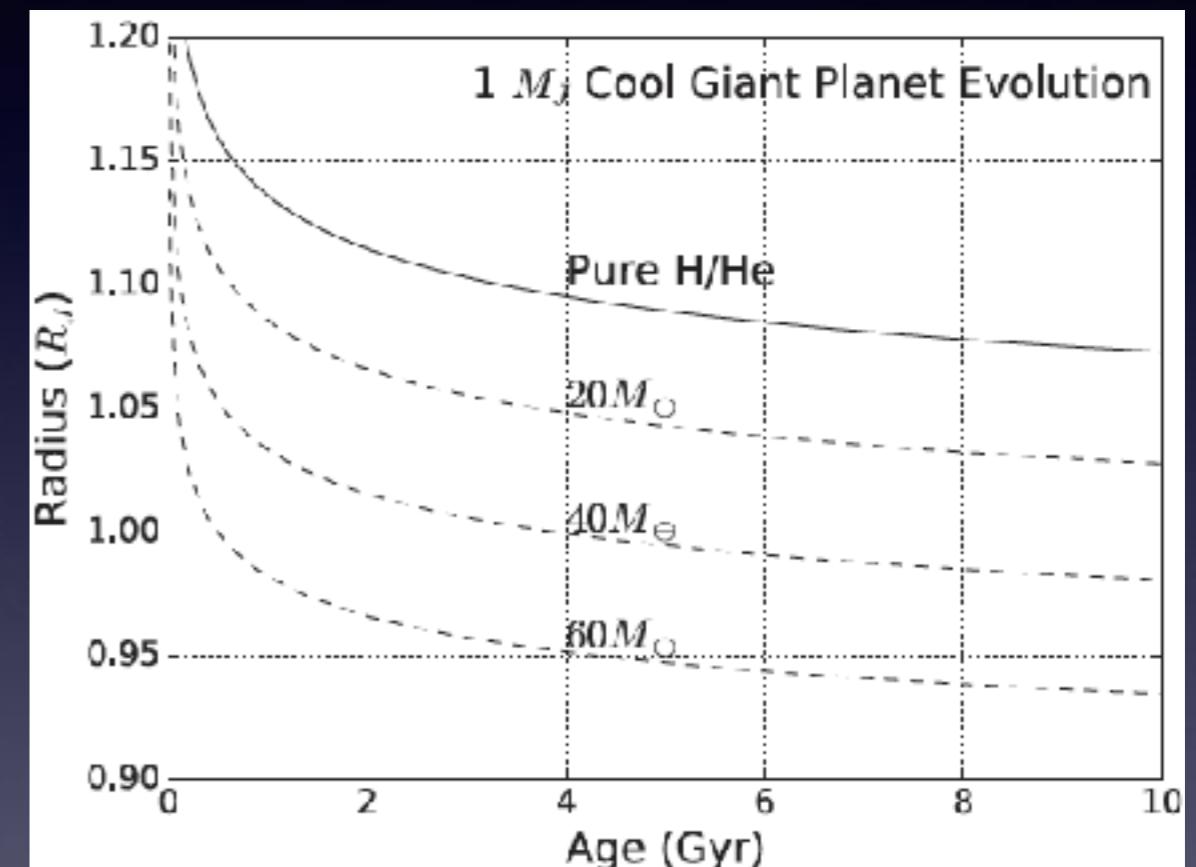
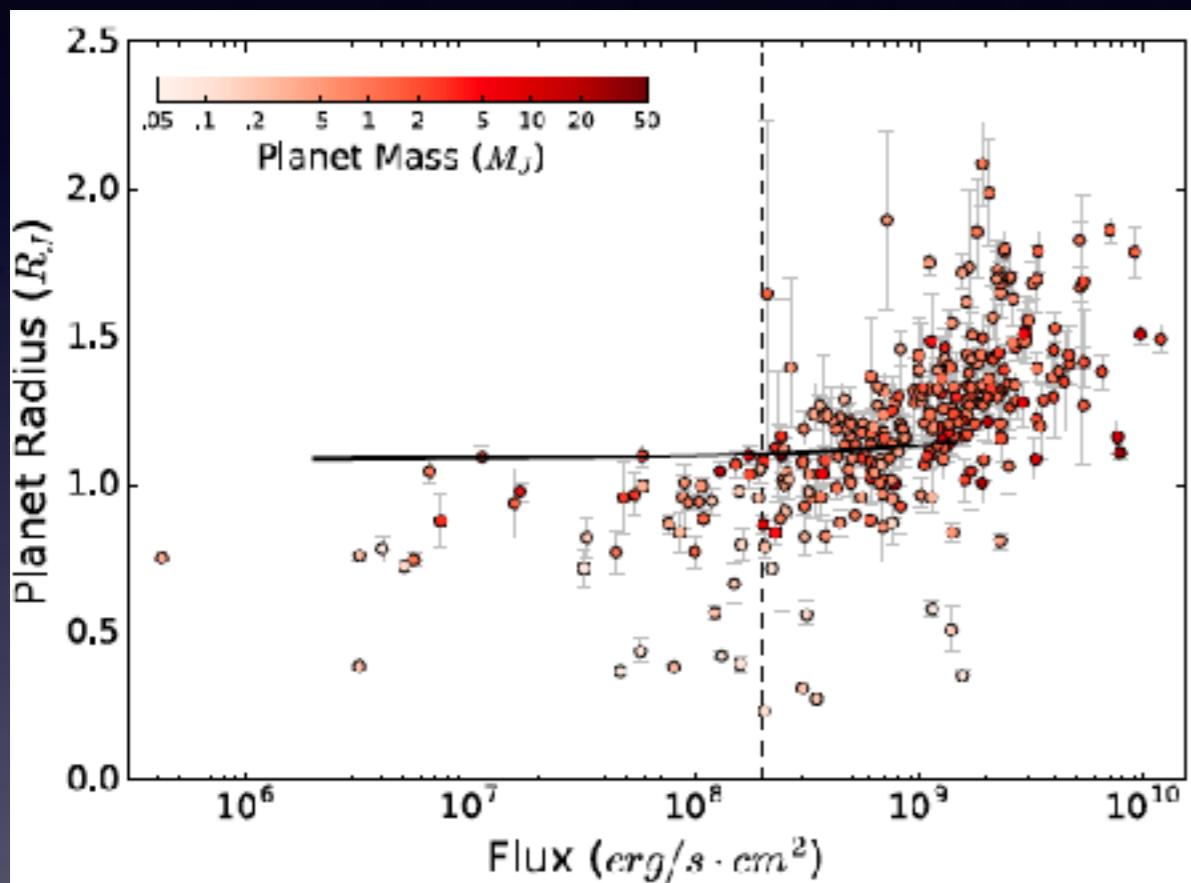


in collaboration with

Geoff Bryden (JPL/Caltech), Masahiro Ikoma (Tokyo Univ),  
Gautam Vasisht (JPL/Caltech), Mark Swain (JPL/Caltech)

# Estimate of the heavy element mass in observed exoplanets

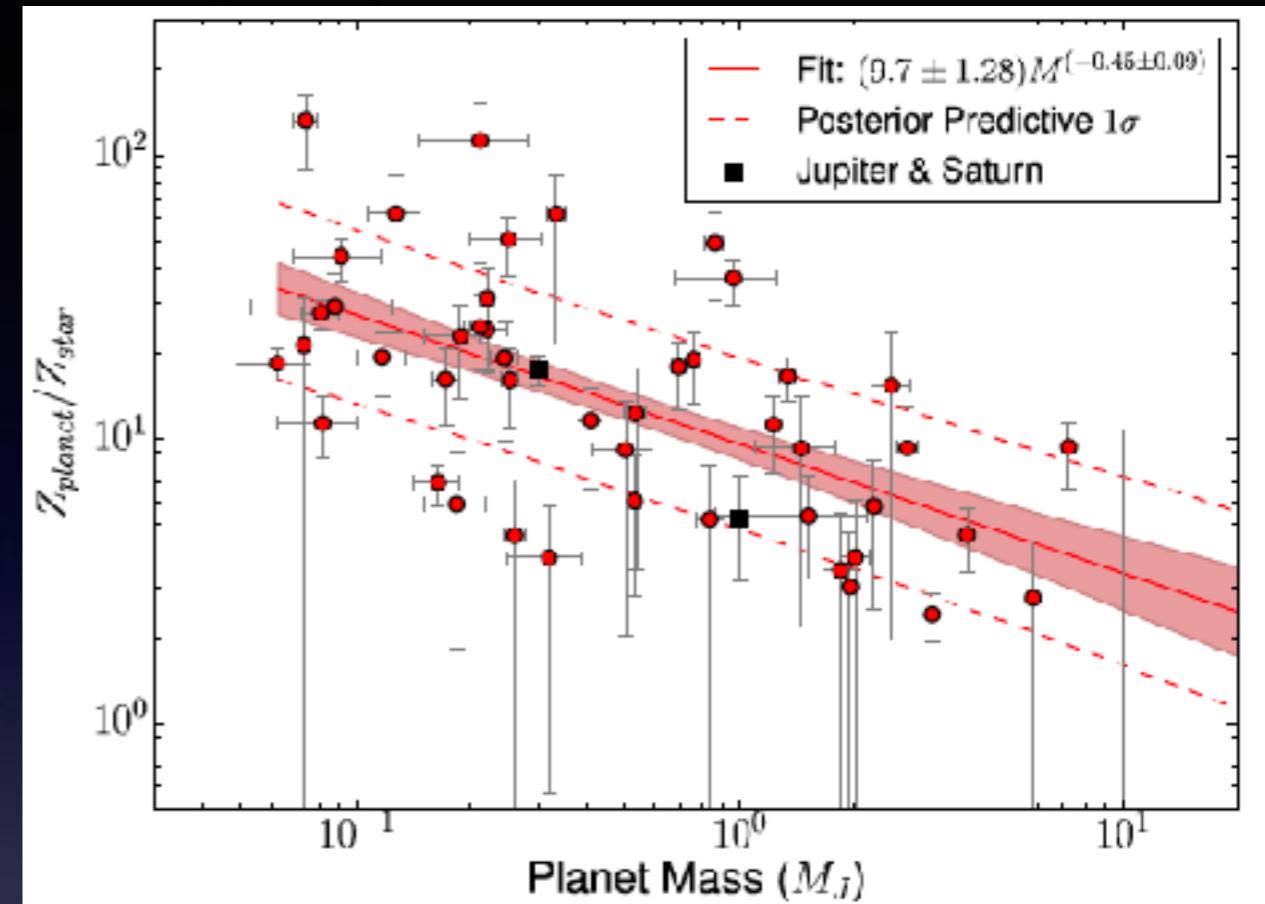
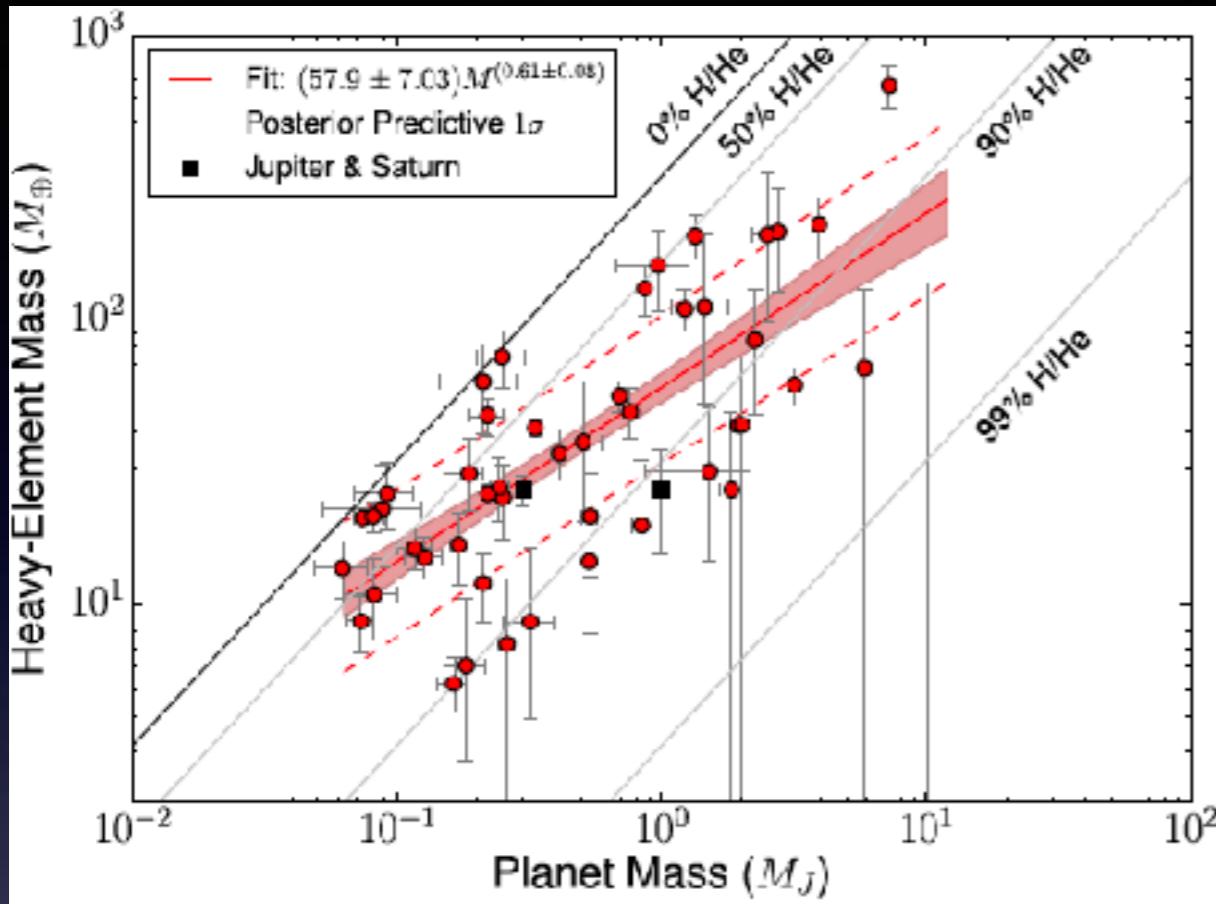
e.g., Guillot et al 2006; Miller & Fortney 2011; Thorngren et al 2016



Target selection: relatively cool close-in exoplanets

Distribute heavy elements in cores and envelopes,  
and compute the radius evolution of planets

# Results of Thorngren et al 2016 (T16)



$$M_Z \propto M_p^\Gamma \text{ with } \Gamma = 0.61 \pm 0.08 \simeq 3/5$$

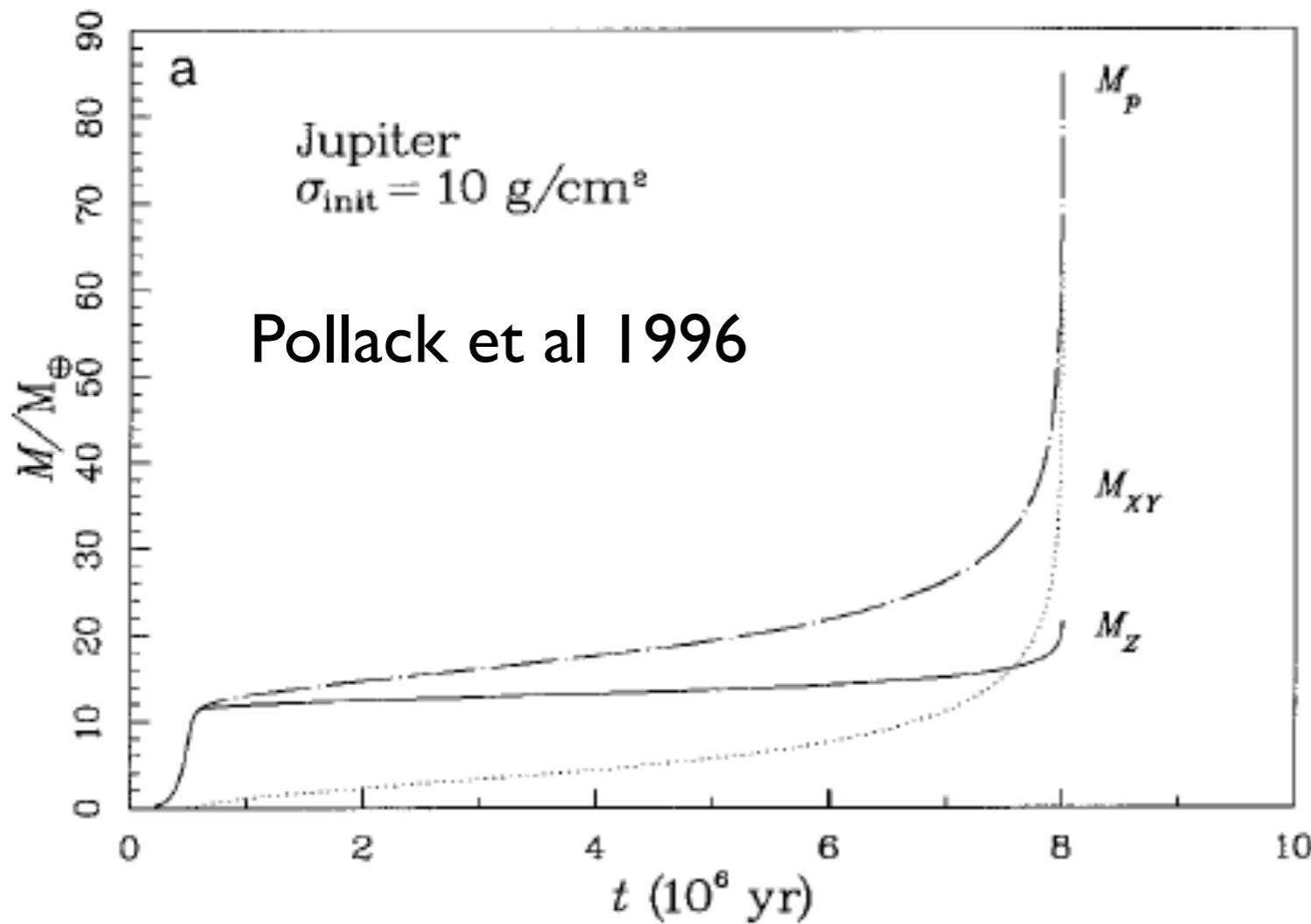
$$\frac{Z_p}{Z_s} = \frac{M_Z}{M_p Z_s} \propto M_p^\beta \text{ with } \beta = -0.45 \pm 0.09 \simeq -2/5$$

$\Gamma - 1 \simeq \beta \Rightarrow M_Z$  and  $M_p$  are almost independent of  $Z_s$

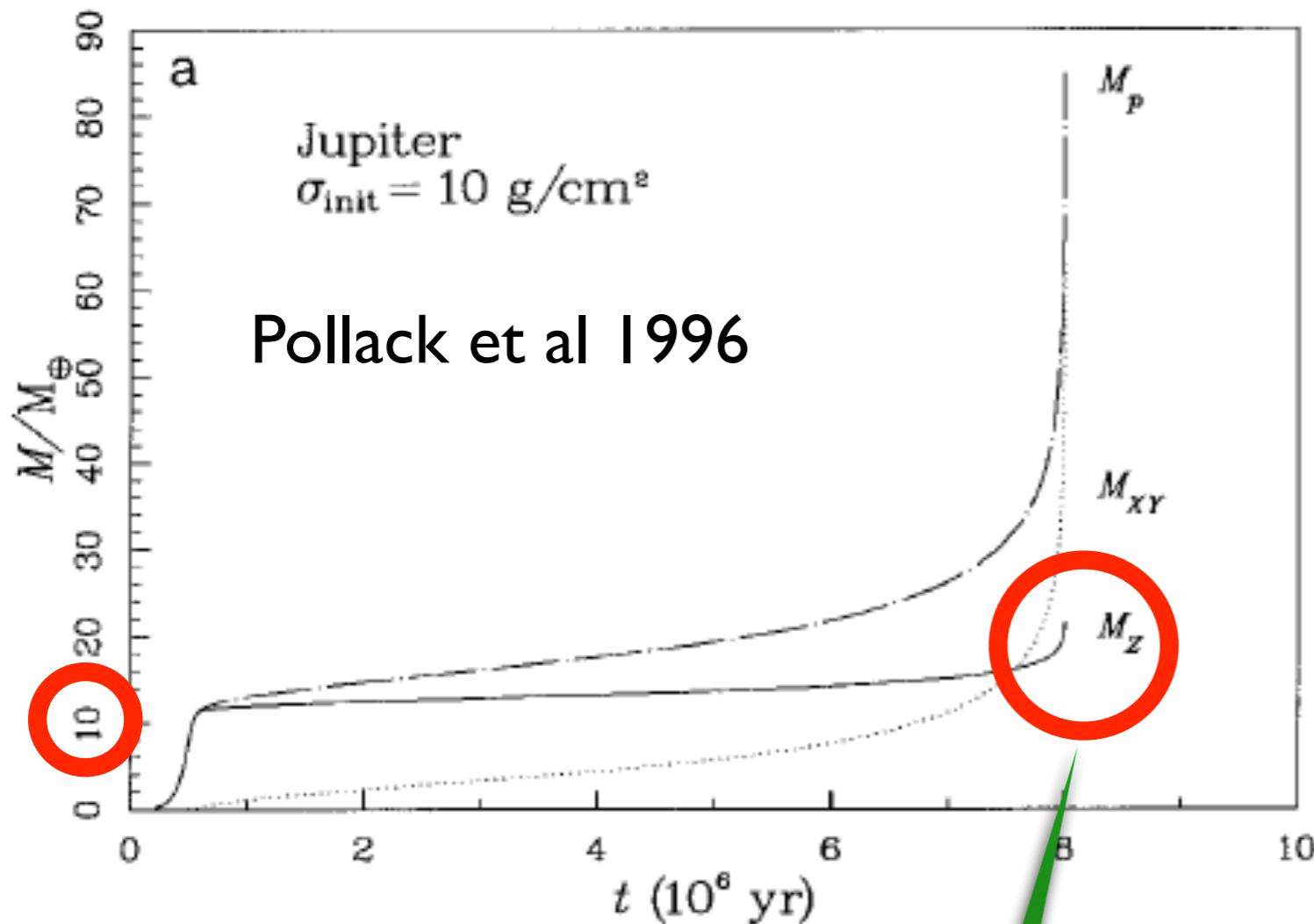
$M_Z$  : the total heavy element mass in planets with the mass of  $M_p$

$Z_s$  : the metallicity of the host star

# Planet Formation via Core Accretion: Accretion of Gas and **Solids**



# Planet Formation via Core Accretion: Accretion of Gas and **Solids**



$$M_p = M_{XY} + M_Z$$

$$M_Z = M_{\text{core}} + M_{\text{pl}} + M_{\text{pe}} + M_{Z,\text{gas}}$$

Planetsimals

Pebbles

dust in gas

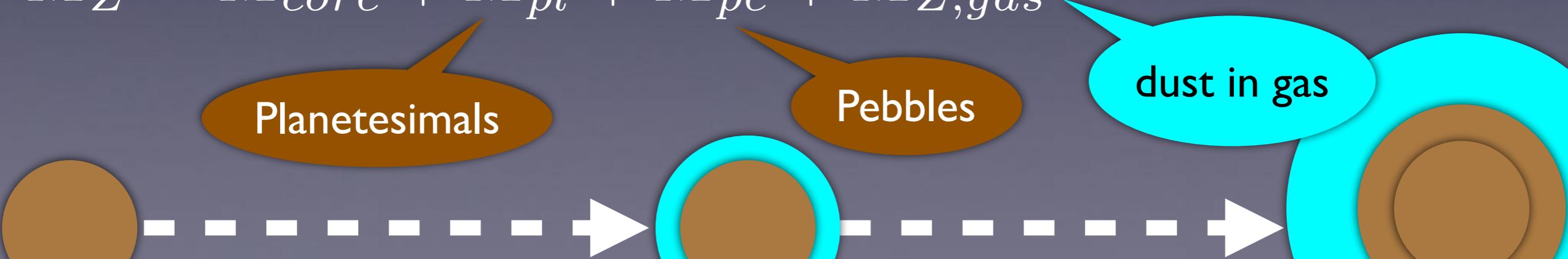


Power-law index	T16	$M_{core}$	$M_{pl}$ (w/o Gap)	$M_{pl}$ (w/ Gap)	$M_{pe}$
$\Gamma(M_Z \propto M_p^\Gamma)$	3/5	0	1/3	3/5	1/3
$\beta(Z_p \propto M_p^\beta)$	-2/5	-1	-2/3	-2/5	-2/3

Gas accretion is limited by disk evolution, following Tanigawa & Ikoma 2007

$$M_p = M_{XY} + M_Z$$

$$M_Z = M_{core} + M_{pl} + M_{pe} + M_{Z,gas}$$



Planetsimals

Pebbles

dust in gas

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Gas accretion is limited by disk evolution, following Tanigawa & Ikoma 2007

Planets accreted solids from **gapped** planetesimal disks  
at the **final** formation stage

$$M_p = M_{XY} + M_Z$$

$$M_Z = \cancel{M_{core}} + \circled{M_{pl}} + \cancel{M_{pe}} + M_{Z,gas}$$

Planetesimals

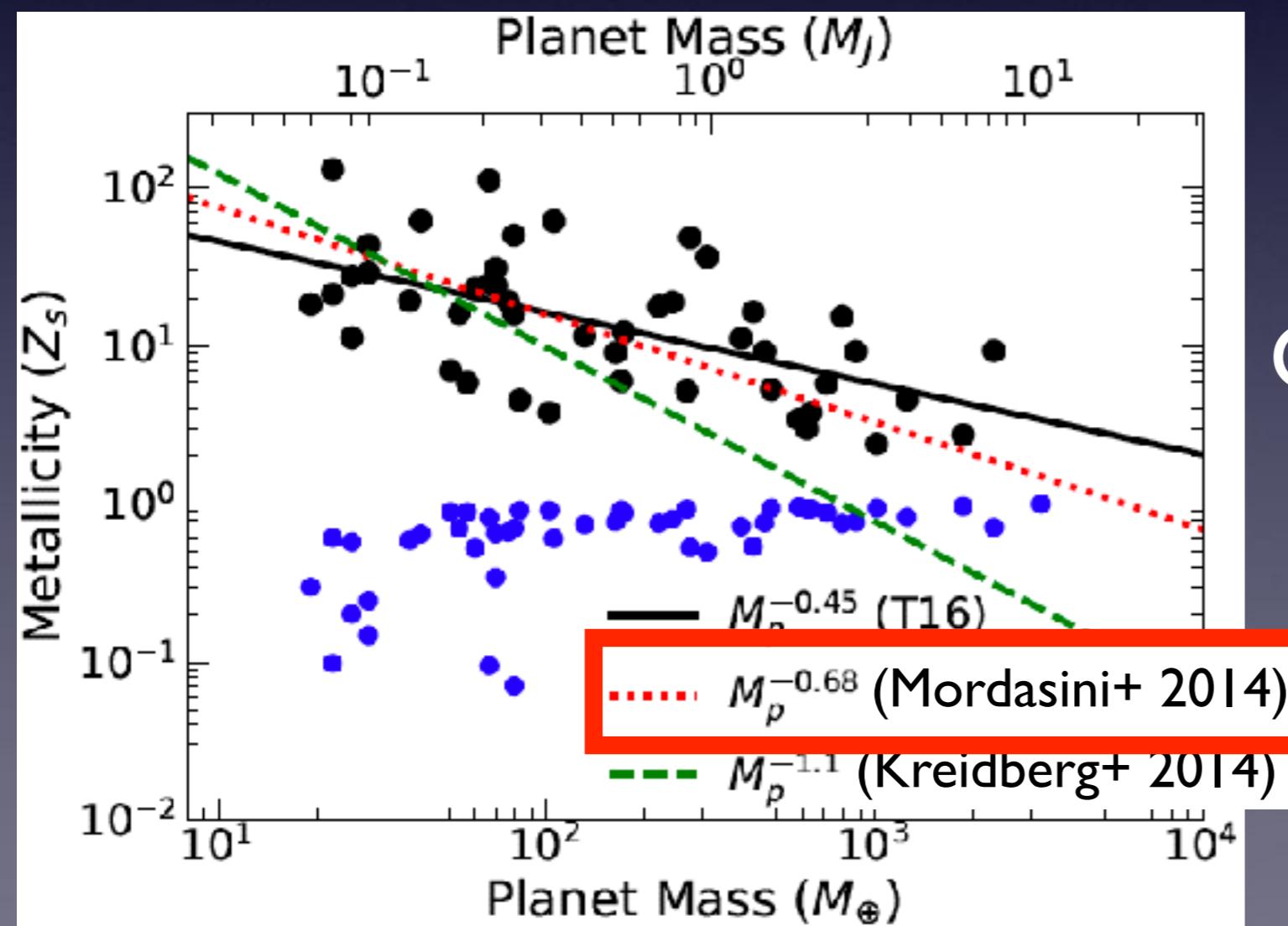
Pebbles

dust in gas



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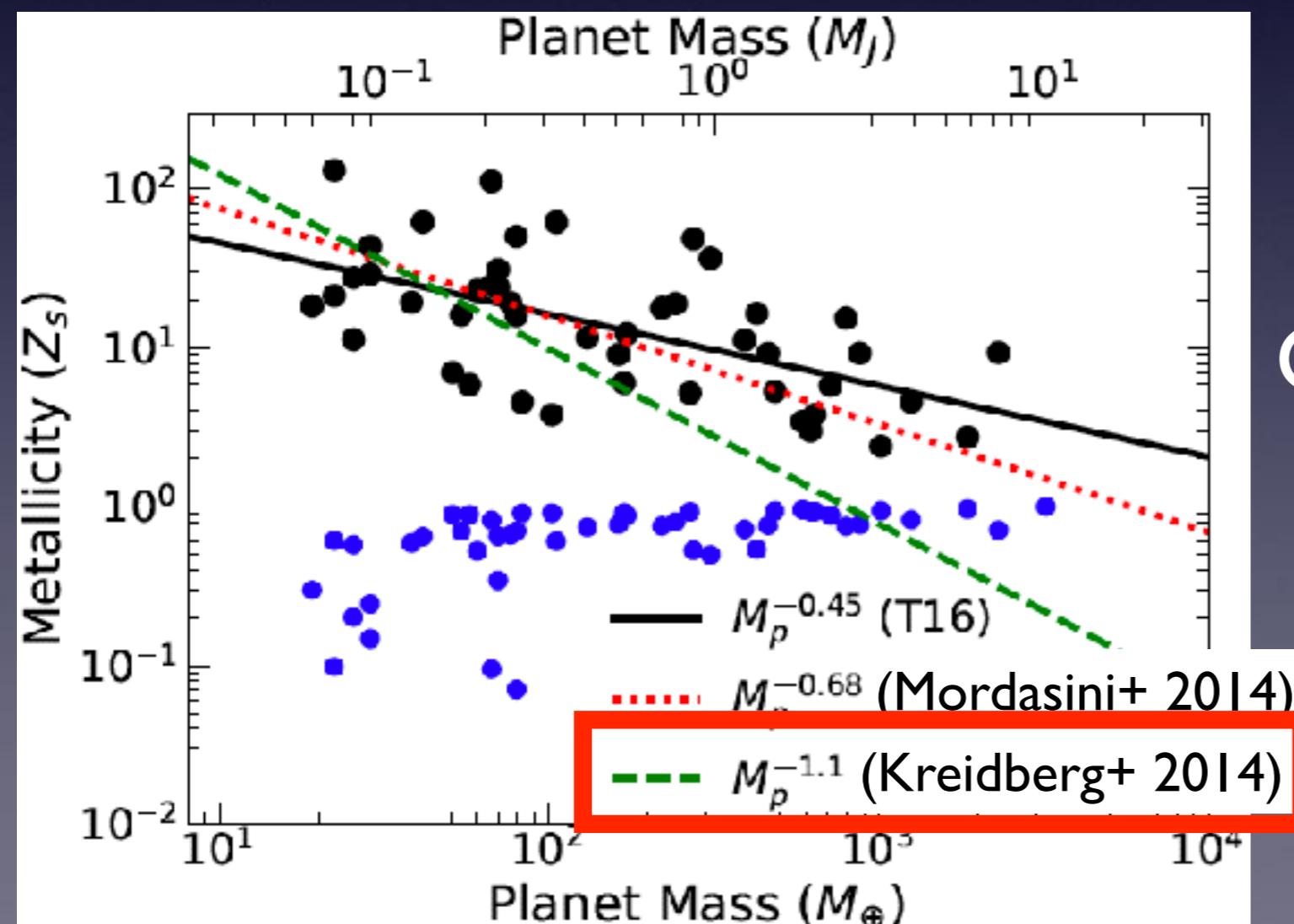


Comparison with previous studies

Our model can reproduce the results of Mordasini

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Gas accretion is limited by disk evolution, following Tanigawa & Ikoma 2007



Comparison with previous studies

Our model can reproduce the results of Mordasini

Evolution of atmospheric metallicities in exoplanets can be explored

# Summary

Hasegawa et al. 2018, ApJ in press  
(arXiv:1807.05305)

- Observed warm Jupiters tend to have correlations:

$$M_Z \propto M_p^{3/5} \quad \frac{Z_p}{Z_s} = \frac{M_Z}{M_p} \frac{1}{Z_s} \propto M_p^{-2/5}$$

- We show that accretion of solids from **gapped planetesimal** disks can reproduce the above trends better
- Our results indicate that core formation, pebble accretion, and dust accretion accompanying gas accretion are **not** important
- Runaway gas accretion is **avoided** for some planets with mass of  $M_p \simeq 20 - 100 M_\oplus$
- Our analysis can **reproduce** the results of detailed population synthesis calculations (Mordasini et al 2014)
- Our results suggest that evolution of **atmospheric metallicities** can be explored in the  $Z_p - M_p$  diagram